arXiv:astro-ph/0010123 5 Oct 2000

Submitted to ApJ Letters

On the Kinematics of GRB980425 and its association with SN1998bw

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ABSTRACT

In this paper I put forward a model in which GRB980425 is both associated with SN1998bw and is also a standard canonical (long; $\sim$ seconds) gamma-ray burst. Herein it is argued that if gamma-ray bursts are relativistic jets with the fastest moving material at the core, then the range of observed jet inclinations to the line-of-sight produces a range in the observed properties of GRBs, i.e. the lag-luminosity relationship. In particular, if the jet inclination is high enough, the observed emitter will move slowly enough to render relativistic beaming ineffective, thus distinguishing the jet from apparent isotropic emission. Thus we expect a break in the lag-luminosity relationship. I propose that GRB980425 defines that break. The position of this break gives important physical parameters such as the Lorentz factor ($\gamma_{max} \sim 1000$), the jet opening angle (~ 1 degree), and thus the beaming fraction ($\sim 10^{-4}$). Estimates of burst rates are consistent with observation. If correct, this model is evidence in favor of the collapsar mode as the progenitor of cosmological, long gamma-ray bursts.

Subject headings: gamma rays: bursts — gamma rays: theory

1. Introduction

GRB980425 and its apparent association with SN 1998bw (Galama et al. 1998) has drawn much attention among gamma-ray burst researchers. While the connection of the gamma-ray burst (GRB) to the supernova (SN) remains uncertain, it is striking that GRB980425 and SN 1998bw were each, taken individually, unusual events.

To start, SN 1998bw was a relatively rare and unusually luminous Type I b/c supernova (Galama et al. 1998). It was the brightest radio supernova ever observed (Waxman & Loeb 1999) which may have been due to relativistic outflow with Lorentz factor $\gamma \sim 2$ (Kulkarni et al. 1998).

Furthermore, GRB980425 was an unusual GRB. It was comprised of a single, unusually rounded peak (Bloom et al. 1998). A cool burst, it was not seen in BATSE's highest energy channel (> 300 keV) (Norris et al. 2000). If this burst is indeed associated with SN1998bw ($z = 0.008$), then the burst is apparently vastly weaker than all other known bursts, with an inferred isotropic gamma-ray energy of 8×10^{47} ergs (Galama et al. 1998). Finally, of particular interest to this paper, Norris et al. (2000) found that the lag of the peak of this burst between BATSE channels 1 and 3 was exceptionally large: $\Delta t_{980425} \approx 4.5$ seconds.

In light of the respective idiosyncrasies of these two events, we may either conclude that we have seen a chance coincidence of two unusual events, with a probability of 10^{-4} or less (Galama et al. 1998), or perhaps the discovery of an entirely new type of GRB (Galama et al. 1998; Bloom et al. 1998).

In this paper I propose a third alternative; that GRB980425/SN1998bw is a canonical gamma-ray burst, deriving from a relativistic jet driven by a collapsar (MacFadyen & Woosley 1999), observed at high angle of inclination. The idea that this burst was a jet viewed off-axis has been proposed by several other authors (Wang & Wheeler 1998; Woosley et al. 1999; Nakamura 1999; Höflich et al. 1999). However in this paper I show how GRB980425 may be a canonical gamma-ray burst by its relation to other bursts on the lag-luminosity relationship discovered by Norris et al. (2000). Thus this burst need not be a distinct class of GRB or a special case of a failed collapsar, polluted with excessive baryon entrainment within the jet (Woosley & MacFadyen 1999). Physical GRB parameters can be gleaned from this identification.

In brief, if we assume that the core of the jet has the highest velocity material and that the velocity monotonically decreases with increasing angle from the core axis, then there will be an angle at which the $1/\gamma$ aperture imposed by relativistic beaming becomes comparable to the angular size θ_0 of the emitting region. At this angle there will be a change in the observed properties of the GRB. In particular, one would expect a break in the lag-luminosity relationship discovered by Norris et al. (2000) and futher interpreted by Salmonson (2000). Herein I show that the peak number luminosity's inverse dependence on spectral lag, $N_{pk} \propto \Delta t^{-1}$, will steepen to $N_{pk} \propto \Delta t^{-3}$. By fitting the Δt^{-3} curve to intersect with GRB980425 one obtains a complete lag-luminosity curve for GRBs which is consistent with observed data (Figure 1). Knowledge of the shape of this curve allows determinations of some key quantities of interest for GRBs; particularly jet opening angle, maximum lorentz factor, and total energy.

2. A Break in the Lag-Luminosity Relation

In Norris et al. (2000) was presented a relationship between the peak luminosity of gamma-ray bursts (GRB) and the pulse time lag between BATSE energy channels. In Salmonson (2000) this correlation was found to be substantially improved when we neglected our poor knowledge of received photon energy, thus taking the correlation between photon number luminosity and pulse time lag. It was found that the inferred isotropic peak number luminosity N_{pk} (photons sec^{-1}) is related to the observed spectral lag between energy channels Δt by

$$N_{pk} = 8.6 \times 10^{56} \Delta t^{-0.98} \ . \tag{1}$$

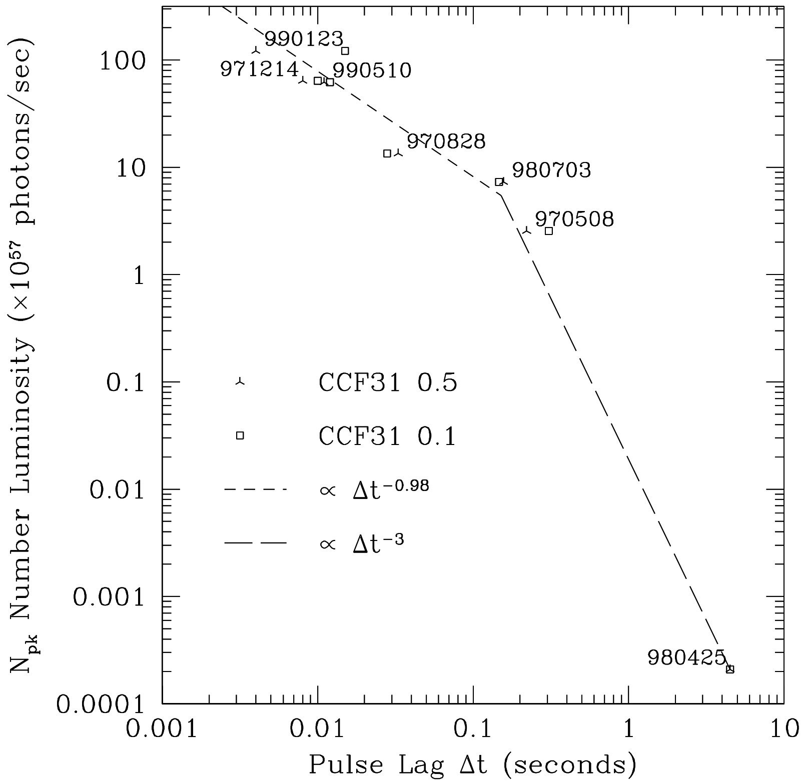

Fig. 1.— Peak photon number luminosity N_{pk} versus spectral pulse lag for six bursts with known redshifts plus GRB980425. A break is inferred by fitting a break slope $\propto \Delta t^{-3}$ to intersect GRB980425. Spectral cross-correlation function lags between BATSE channels 3 and 1 (CCF31) for regions down to 0.5 and 0.1 of peak intensity were obtained from Norris et al. (2000). The line of best fit for 0.1 (squares) is $\propto \Delta t^{-0.98}$.

In Salmonson (2000) was presented a kinematic interpretation of the origin of this relation. Specifically, bursts with emitting material moving with a higher velocity toward the observer appear more luminous and have shorter observed lag (derived from an intrinsic pulse cooling timescale) between observed energy channels due to relativistic blue shift. Relativistic beaming allows one to only consider emitters moving directly toward the observer. I proposed that the wide range of observed (cosmological redshift compensated) spectral lags and inferred luminosities (see Figure 1) could be explained if GRBs derive from a relativistic jet in which the fastest material moves along the core of the jet and the velocity of the material monotonically decreases with increasing angle from the jet axis. The variety of observed bursts then derives from our perspective of the jet. All of the material is assumed to move relativistically ($\gamma \gg 1$) and so all of our received flux is derived from a very small $\sim 1/\gamma^2$ solid angle of the jet; much smaller than the jet opening angle ($1/\gamma \ll \theta_0$). It is from this small region that all of our information about a burst is derived.

The question then arises: what happens when the jet is observed at such large angles from its central axis that the observed emitting material is moving at 'slow' enough velocity that the $1/\gamma$ beaming angle becomes comparable to the diametric angular size of the emitter ($\theta_0 \sim 2/\gamma$)? At this point the size and extent of the emitting region becomes directly observable. In the relativistic case ($\gamma \gg 1$), the received flux emits from an *apparent* region of size R_s/γ where R_s is the emitter distance from the center of the source. If γ is small such that $1/\gamma > \theta_0 \equiv R_e/R_s$, where R_e is the size of the emitting region, then the received flux emits from the entire physical size of this region R_e, i.e. the physical extent of the jet becomes observable.

Using this distinction one can derive the dependence of the inferred isotropic number luminosity $N \propto f_N R^2$ on Lorentz factor for the two cases, where number intensity $f_N = \gamma^3 f'_N$. The relativistic N_{rel} scales as

$$N_{rel} \propto (\gamma^3 f'_N)(R_s/\gamma)^2 \propto \gamma \quad \text{for } 1/\gamma < \theta_0/2 \tag{2}$$

and the sub-relativistic $N_{sub-rel}$ scales as

$$N_{sub-rel} \propto (\gamma^3 f'_N) R_e^2 \propto \gamma^3 \quad \text{for } 1/\gamma > \theta_0/2\ . \tag{3}$$

Thus, taking the observed spectral lag dependence $\Delta t_{obs} \propto 1/\gamma$ (Salmonson 2000) one gets

$$N_{rel} \propto \Delta t^{-1} \quad \text{for } 1/\gamma < \theta_0/2 \tag{4}$$

$$N_{sub-rel} \propto \Delta t^{-3} \quad \text{for } 1/\gamma > \theta_0/2\ . \tag{5}$$

Thus if GRBs are jets, one can expect a break in the lag-luminosity relationship. This is analogous to the expected break in the lightcurve of a GRB afterglow as it transitions from relativistic to sub-relativistic expansion (Rhoads 1997).

The inclusion of GRB980425 into the set of all long GRBs is the simplest explanation; one need not invoke a separate phenomenon to explain a burst so vastly weaker than its cosmological counterparts. The model presented here unifies these seemingly disparate events by way of a single mechanism; observer perspective on a relativistic jet. For GRB980425 to be a member of the set of known bursts, it must be in the sub-relativistic regime. Thus I fit the $N_{sub-rel}(\Delta t)$ curve to contain GRB980425. The result is a complete lag-luminosity relationship for long GRBs and is shown in Figure 1. Although the data is as yet very sparse, it is consistent with the curve.

The intersection of the $N_{rel}(\Delta t_{obs})$ and $N_{sub-rel}(\Delta t_{obs})$ curves is at

$$N_{int} = 5.5 \times 10^{57} \text{ photons sec}^{-1} \tag{6}$$

$$\Delta t_{int} = 0.15 \text{ sec}\ . \tag{7}$$

At this point the jet and beaming angles are the same, $\theta_0 = 2/\gamma$. As in Salmonson (2000)

$$\frac{\gamma_{int}}{\gamma_{980425}} = \frac{\Delta t_{980425}}{\Delta t_{int}} = \frac{4.5 \text{ sec}}{0.15 \text{ sec}} = 30 \tag{8}$$

so $\gamma_{int} = 30\gamma_{980425}$. Similarly for the brightest burst in this dataset, $\Delta t_{990123} \simeq 0.01$, so $\gamma_{990123} \simeq 450\gamma_{980425}$. The value of γ_{980425} is uncertain. Bounds will be discussed in the next section, but for now we take $\gamma_3 \equiv \gamma_{980425}/3$. Thus the brightest, fastest bursts such as GRB990123 have Lorentz factors $\gamma_{max} \sim 1000\gamma_3$ or higher, while more middling bursts such as GRB980703 have $\gamma \sim 100\gamma_3$.

The diametric opening angle of the jet is

$$\theta_0 \equiv \frac{2}{\gamma_{int}} = \frac{2}{90\gamma_3} \simeq \frac{1.3^o}{\gamma_3} . \tag{9}$$

In Salmonson (2000) it was estimated that $\theta_0 \sim (5^o \text{ to } 10^o)/\gamma_{100}$ where $\gamma_{100} \equiv \gamma_{max}/100$, which is in agreement with the value presently calculated.

Having knowledge of the opening angle of the jet, $\theta_0 \simeq 1/45/\gamma_3$, we may calculate the beaming factor

$$\begin{aligned} f_\Omega &= 1 - \cos\left(\text{Arcsin}\left(\frac{1}{\gamma}\right) + \frac{\theta_0}{2}\right) \\ &\simeq \tfrac{1}{2}\left(\frac{\theta_0}{2}\right)^2 = 6.4\gamma_3^{-2} \times 10^{-5} \end{aligned} \tag{10}$$

where $1/\gamma \ll \theta_0/2 \ll 1$ for cosmological GRBs. The total energy in γ-rays is related to the inferred isotropic energy by $E_{tot} = f_\Omega E_{iso}$. This is a large reduction in the energy required to make a GRB. For instance, GRB990123 had $E_{iso} = 2 \times 10^{54}$ ergs (Galama et al. 1999) and thus $E_{tot} = 1.2\gamma_3^{-2} \times 10^{50}$ ergs. So γ-ray energies of bursts are a fraction of the total collapsar energy.

3. Event Rate Estimation

Having derived the above quantities, one can now make some crude estimations of rates of GRBs and SNe Ib/c. First, what fraction of SNe Ib/c make GRBs? Woosley & MacFadyen (1999) estimate that 1% of SNe Ib/c have large enough helium cores to make a collapsar SN-GRB. Bloom et al. (1998) estimate the SN Ib/c rate to be 0.3/day out to distance of $100h_{65}^{-1}$ Mpc, which is roughly the limiting distance for a GRB980425 to be seen by BATSE. Thus one expects 0.003/day $\sim$ 1/year GRB rate within this distance. Norris et al. (1999, see their Fig. 2) find that the number of bursts similar to GRB980425 and with comparable lags comes to roughly $\sim$ 1/year, consistent with this estimate.

A lower bound for our rate can give information on the Lorentz factor of γ_{980425}. The beaming factor $f_\Omega = 1 - \cos(\text{Arcsin}(1/\gamma) + \theta_0/2)$ gives the probability of observing an event's jet. Since $1/\gamma \gg \theta_0$ for GRB980425, $f_\Omega \approx 1 - \sqrt{1 - 1/\gamma^2} = 1 - v/c \sim 1/2/\gamma^2$ where v is the speed. Since we estimate a SN-GRB rate of 1/yr within 100 Mpc, the inverse average number of years between detected SN-GRBs estimates f_Ω which, in turn, gives a weak (due to incompleteness of SN-GRB detections) lower bound on γ. For instance, if $\gamma = 5$, then $f_\Omega = 0.02$, and we can expect a burst like GRB980425 every ~ 50 years. For $\gamma = 2$ and 3 one gets 7 and 17 years respectively. Bloom et al. (1998) and Norris et al. (1999) find little evidence for another convincing SN-GRB event in the BATSE catalog. Firstly, this is not a problem; GRB980425-like events are likely rare enough to have been missed or not exist during BATSE mission duration. Secondly, assuming completeness (a poor assumption) the data begins to push the lower bound on γ up to around 2 or 3. Kulkarni et al. (1998) argue for a radio emission source moving with $\gamma \sim 2$, while Woosley & MacFadyen (1999) suggest that $\gamma \approx 5$ could have created GRB980425. These values likely bracket the real value. Thus in this paper I assume $\gamma_{980425} \sim 3$.

At cosmological distances, taking the above rate of GRB generating SNe, one gets a rate out to radius r

$$\begin{aligned} \mathrm{Rate}(r) &\sim f_\Omega \; 3 \times 10^{-3}/\mathrm{day} \left(\frac{r}{100\mathrm{Mpc}}\right)^3 \\ &= 0.2/\mathrm{day} \left(\frac{r}{10\mathrm{Gpc}}\right)^3 . \end{aligned} \tag{11}$$

using Eqn (10). This is consistent with the ~ 1 GRB/day observed by BATSE. Much better modeling including cosmology and star formation rates can be done. However, the point to make here is that it is consistent that GRB980425 and the cosmological bursts derive from the same progenitor.

4. Discussion

The obvious prediction of the model present herein is that all (long) GRBs will fall along the curve in Figure 1. In addition, since this model supports the collapsar model for GRB progenitors, all (long) GRBs should have a SN buried within as predicted by Woosley & MacFadyen (1999).

Many questions remain. For instance GRB980425 had a quickly decaying X-ray afterglow (Bloom et al. 1998). Perhaps numerical simulations of afterglows from relativistic jets (e.g. Granot et al. 2000) could yield insights into this behavior. If this is a common characteristic of off-axis jets, this might have an effect on the predicted rates of observable so called "orphan afterglows" (Rhoads 1997).

This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

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